

X-ray source populations in the Magellanic Clouds

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Abstract. Early X-ray surveys of the Magellanic Clouds (MCs) were performed with the imaging instruments of the Einstein, ASCA and ROSAT satellites revealing discrete X-ray sources and large-scale diffuse emission. Large samples of supernova remnants, high and low mass X-ray binaries and super-soft X-ray sources could be studied in detail. Today, the major X-ray observatories XMM-Newton and Chandra with their advanced angular and spectral resolution and extended energy coverage are ideally suited for detailed population studies of the X-ray sources in these galaxies and to draw conclusions on our own Galaxy. We summarize our knowledge about the X-ray source populations in the MCs from past missions and present first results from systematic studies of the Small Magellanic Cloud (SMC) using the growing number of archival XMM-Newton observations.

1. Introduction

The study of X-ray source populations and diffuse X-ray emission in nearby galaxies is of major importance in understanding the X-ray output of more distant galaxies as well as learning about processes that occur on interstellar scales within our own Galaxy. The MCs, satellites of the Milky Way, show different chemical compositions, are irregular in shape, and are heavily interacting with the Milky Way. This influences the process of star formation and the study of stellar populations in the MCs is particularly rewarding. Their proximity makes the MCs the ideal galaxies for X-ray studies.

Previous X-ray surveys of the MCs, which were performed with the imaging instruments of the Einstein, ASCA and ROSAT satellites, revealed discrete X-ray sources and large-scale diffuse emission. The early Einstein observations unveiled more than one hundred point-like sources in the Large Magellanic Cloud (LMC; Long et al., 1981; Wang et al., 1991) and seventy in the SMC (Wang & Wu, 1992). ASCA found more than 100 sources and detected coherent pulsations from 17 sources in the SMC (Yokogawa et al., 2003). In particular the high sensitivity and the large field of view of the ROSAT

PSPC provided the most comprehensive catalogues of discrete X-ray sources in the directions of the LMC (758 in an area of ~ 59 square degrees; Haberl & Pietsch, 1999) and the SMC (517 in an area of ~ 18 square degrees; Haberl et al., 2000). Together with ROSAT HRI observations this yielded about 1000 and 550 X-ray sources in the areas of the LMC and SMC, respectively (Sasaki et al., 2000a,b). A spectral analysis of the emission from the hot thin plasma in the interstellar medium (ISM) using ROSAT PSPC data of the MCs revealed temperatures between 10^6 and 10^7 K (Sasaki et al., 2002).

Complementary deep surveys at other wavelengths were carried out by, e.g., *Galex* (UV) and *Spitzer* (IR), together with ground-based observations of H α , H I and radio continuum. In the optical/NIR bands the principal large scale digital surveys of the MCs are the microlensing surveys (MACHO and OGLE), the bright star survey of Massey (2002), the MCPS Magellanic Clouds Photometric Survey (Zaritsky et al., 2002) and the DENIS and 2MASS near infra-red surveys. Combining the available information from the different wavelength bands allows to characterize the properties of different X-ray source classes like supernova remnants (SNRs), high and low mass X-ray binaries (HMXBs, LMXBs) and super-soft X-ray sources (SSSs) and differentiate them from background sources (mainly active galactic nuclei, AGN) or foreground stars. For the classification of sources X-ray spectral information (hardness ratios), X-ray to optical flux ratio, angular extent and flux variability can be used (e.g., Haberl et al., 2000; Yokogawa et al., 2003; Shtykovskiy & Gilfanov, 2005; McGowan et al., 2007a,b). This has also been demonstrated for other Local Group galaxies like M31 (Pietsch et al., 2005b) and M33 (Pietsch et al., 2004).

2. Source populations

The SMC is very rich in HMXBs, which can be used as tracers of recent star formation in the galaxy. The evolutionary age of these early type binary systems is low (Grimm et al., 2003) and most of the Be-HMXBs in the SMC are found in regions with young (20–50 Myr) stellar

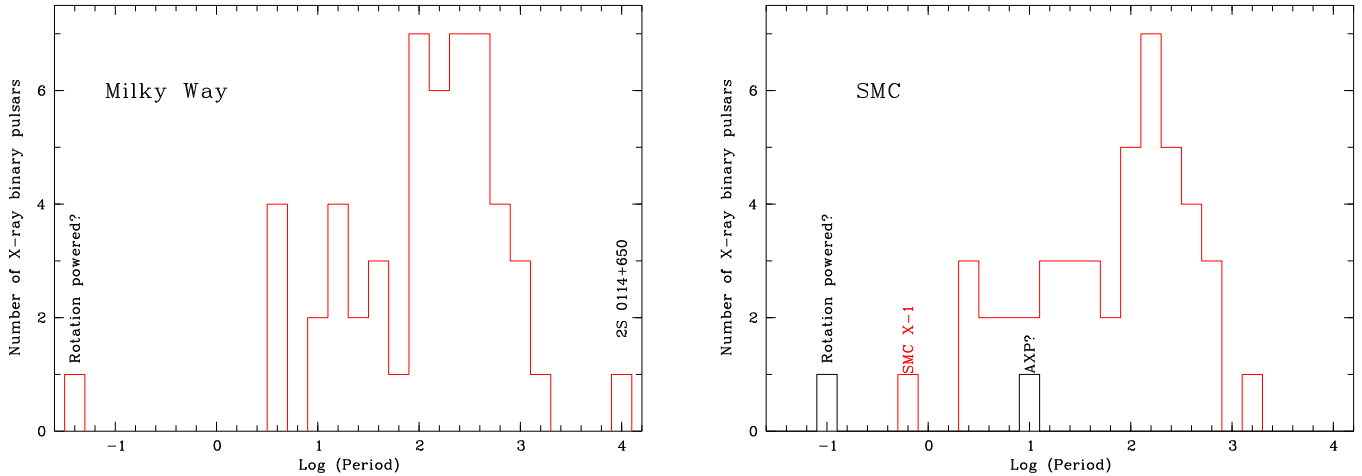


Fig. 1. Comparison of the pulse period distribution of HMXB pulsars in the Milky Way and the SMC. Despite the large difference in galaxy mass, nearly as many HMXB pulsars are known (status beginning of 2006) in the Milky Way (53) and the SMC (46). In both galaxies most of the pulsars are found with spin periods between 100 s and 1000 s. The fraction of pulsars with spin periods between 1 s and 100 s is slightly higher in the SMC as compared to the Milky Way.

populations (Shtykovskiy & Gilfanov, 2007). About fifty HMXB pulsars are now known in the SMC together with many more candidates which exhibit similar X-ray properties, but yet without detected pulsations which reveal the spin period of a neutron star (e.g., Haberl & Sasaki, 2000; Haberl & Pietsch, 2004). Such a large number of HMXBs can be used for statistical studies, e.g. for a comparison with the HMXB population in the Milky Way (see Fig. 1). In nearly all cases in the SMC the mass donor star is a Be star (Coe et al., 2005) with a circum-stellar disc (Okazaki & Negueruela, 2001). When the binary orbit is wide and eccentric, the passage of the neutron star close to the disc results in X-ray outbursts and a transient behaviour of the Be-HMXBs. Many of the Be-HMXBs in the SMC were discovered during outburst (often exceeding 10^{37} erg s $^{-1}$ in X-ray luminosity), in particular with ASCA (Yokogawa et al., 2003) and RXTE (for results from a regular monitoring of the SMC see Laycock et al., 2005).

The X-ray spectra of many HMXBs show, in addition to the typical power-law, a low-energy emission component. The origin of this soft excess is not clear yet (Hickox et al., 2004). The Be-HMXBs in the SMC are ideally suited to investigate the soft part of their spectra due to the low foreground absorption, in contrast to HMXBs in the Milky Way which are mainly found in the galactic plane suffering high absorption. The best case to study the soft spectral component so far is probably the Be-HMXB RX J0103.6–7201 (with 1323 s the pulsar with the longest period known in the SMC) which showed during one XMM-Newton observation a highly absorbed power-law component and a completely disentangled soft component. The soft component can be reproduced by thermal plasma emission with its luminosity strongly correlated

with the total intrinsic source luminosity, suggesting that the same mechanism is responsible for the generation of the soft emission (Haberl & Pietsch, 2005).

Luminous super-soft X-ray sources were discovered with the Einstein observatory (CAL 83 and CAL 87) and were established as a new class of X-ray binaries after the ROSAT discoveries of five new such objects in the LMC (Kahabka et al., 1994; Greiner, 1996). SSSs exhibit very soft X-ray spectra (characteristic temperatures kT of a few tens of eV) and show a variety of intensity variations on different time scales (little variations, slow exponential decay over years, transient outbursts, off-states). The most popular model for SSS involves nuclear burning on the surface of an accreting white dwarf (WD) which can explain the observed luminosities (van den Heuvel et al., 1992; Kahabka & van den Heuvel, 1997). The WDs in SSS indicate an older population consistent with their distribution mainly in the outer parts of the MCs. After the detection in the MCs, SSSs were also found in other local group galaxies. Interestingly the majority of SSSs in M31 was identified with optical novae (Pietsch et al., 2005a) which enter a SSS state some time after optical outburst with onset and duration of the SSS state varying strongly from source to source. The MCs are sufficiently close to detect SSSs at low luminosities which allows us to address the question if permanently low-luminosity (too low for the high accretion rates inferred from the models) SSSs exist, or if they are highly variable which could point to unstable nuclear burning. XMM-Newton observations of faint SSSs in MC fields show that this class is composed of very different objects (Kahabka & Haberl, 2006; Kahabka et al., 2006; Orio et al., 2007; Kahabka et al., 2008). Symbiotic stars, central stars of planetary nebulae and even a Be star

(Kahabka et al., 2006) were identified as optical counterparts. Be/WD systems are predicted to be more numerous than Be/neutron star binaries and the fact that we have so far not discovered any clear Be/WD case needs to be explained by binary evolution models.

SNRs are a major source of matter feedback into the ISM. Supernova explosions correlated in space and time generate super-bubbles (SBs) typically hundreds of parsecs in extent. SNRs and SBs are among the prime drivers controlling the morphology and the evolution of the ISM. A synoptic study of thirteen SMC SNRs observed by XMM-Newton (van der Heyden et al., 2004) showed a range of different morphological features from shell-like to more irregular structures. A spectral analysis with single-temperature non-equilibrium ionization (NEI) and Sedov models revealed the different evolutionary phases of the remnants.

3. XMM-Newton observations of the SMC

Up to now, no complete X-ray survey of the SMC exists with the currently operating large observatories Chandra or XMM-Newton. A partial survey concentrating on the Eastern Wing (McGowan et al., 2007a), was performed by Chandra. These observations covered areas in the outer parts of the SMC, and the majority of the 523 detected sources were identified as AGN, while the abundance of HMXBs (four detected pulsars) is low compared to the SMC Bar (McGowan et al., 2007b). XMM-Newton observations were dedicated to various individual targets in the SMC resulting in a very inhomogeneous coverage. In a first attempt to derive the luminosity function of HMXBs in the SMC, Shtykovskiy & Gilfanov (2005) analyzed the (mainly EPIC-MOS) 2–8 keV data of nine observations and compared the observed number of HMXBs with predictions based on star formation rate (SFR) estimates. Depending on the SFR indicators used, the abundance of SMC HMXBs can be consistent with that of the Milky Way and other nearby galaxies or as much as a factor of ten higher.

Meanwhile many more XMM-Newton observations are available in the direction of the SMC. To obtain an interim XMM-Newton view of the SMC we systematically analyzed all available EPIC data (the pn camera either in full frame (FF), extended full frame (eFF) or large window (LW) mode). This includes eight own proprietary observations from AO5 and AO6 together with all public archival data. After removing three observations which suffered from very high background, there remain 38 observations which we used for our analysis. Fourteen of them are calibration observations in the direction of 1E 0102.2-7219 which accumulate to a deep exposure in the north-eastern region. A mosaic RGB colour image is presented in Fig. 2 which is produced from 38 pointings which mainly cover the Bar and the Eastern Wing of the SMC (three observations are pointed further south around the RS CVn type

variable CF Tuc). The image includes data from four observations with slightly increased background which are not well suited for a clean image and the analysis of diffuse emission, but can still be used for the analysis of point sources. In the following we present a few examples of our first results with the emphasis on SNRs and HMXBs.

Three additional known SNRs – SNR B0039–73.9 = HFPK 530 (Filipovic et al., 1998; Haberl et al., 2000; Payne et al., 2007), SNR B0050–72.8 and SNR B0058–71.8 (Mathewson et al., 1984) – are covered by new XMM-Newton observations. This allows to extend the investigations of SMC SNRs by van der Heyden et al. (2004). The three SNRs are located outside the main star forming regions where the majority of SNRs is found (north-east and south-west ends of the SMC Bar, see Dickel et al., 2001; van der Heyden et al., 2004). All three show irregular X-ray morphologies with low surface brightness. An analysis of the X-ray spectra with a single-temperature NEI model reveals relatively low temperatures around $kT = 0.18$ keV, suggesting that these are older remnants.

A new candidate SNR is proposed from its X-ray colours. It was already detected by Haberl et al. (2000) in ROSAT PSPC data (source 334 in their catalogue is listed with an extent of $\sim 18''$ and correlates with a radio source, consistent with emission from a SNR) and following van der Heyden et al. (2004) we name it HFPK 334. Filipovic et al. (2008, in preparation) will present multi-wavelength morphological studies and more detailed results from the X-ray spectral analysis of the three SNRs, mentioned above, and the new candidate.

The X-ray transient XTE J0103-728, discovered as 6.85 s pulsar by RXTE, was seen in outburst at a 0.2–10 keV luminosity of 1.6×10^{37} erg s $^{-1}$ in October 2006. The EPIC data allowed us to accurately locate the source and to investigate its temporal and spectral behaviour. The identification with a Be star confirms XTE J0103-728 as Be/X-ray binary in the SMC (Haberl et al., 2007). At least four new HMXB pulsars (Haberl et al. 2008, in preparation) are discovered. Their optical counterparts are identified with stars in the optical SMC surveys which show optical brightness and colours consistent with Be stars.

We performed a systematic source detection on the images obtained from the individual observations (five energy bands for each of the three EPIC instruments). In total more than 1650 detections were obtained from the 38 analyzed observations. This results in about 1060 individual sources. The total detection list can be used for time variability studies for about 200 sources which are detected more than once. The faintest sources have count rates as low as 1.3×10^{-3} cts s $^{-1}$ (0.2–4.5 keV) in comparison to the brightest source (the SNR 1E 0102.2-7219) with a pn count rate of 31 cts s $^{-1}$. Assuming a canonical HMXB spectrum (photon index 1.0, absorption column density 10^{21} cm $^{-2}$) this translates into a typical flux limit (for detection) of 3.7×10^{-15} erg cm $^{-2}$ s $^{-1}$ or a source lu-

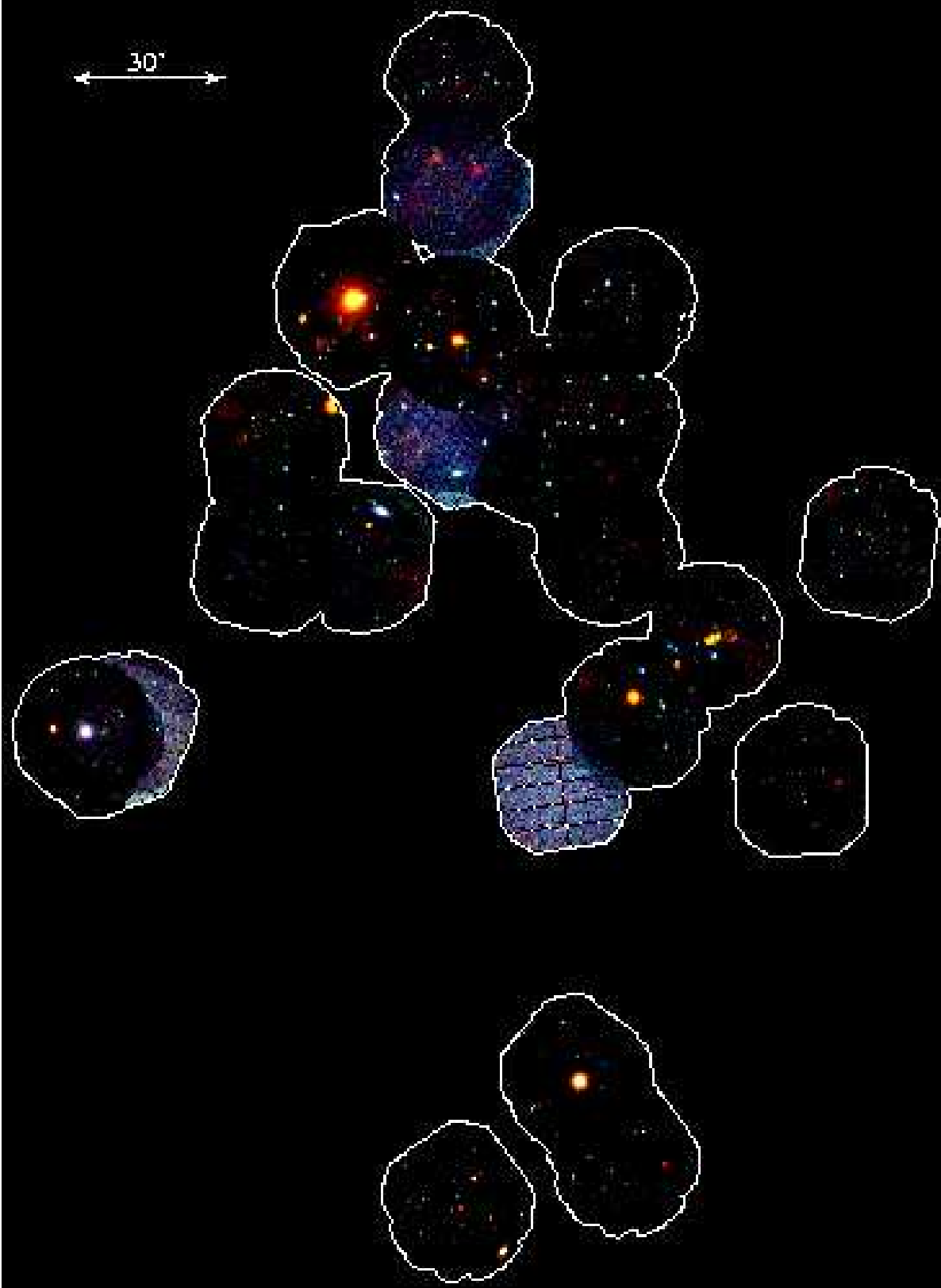


Fig. 2. EPIC mosaic image of the SMC region obtained from the data of 35 individual observations. The RGB colour image is composed of images from the three energy bands 0.2 – 1.0 keV, 1.0 – 2.0 keV and 2.0 – 4.5 keV and from all three EPIC instruments. The individual images are exposure corrected and out-of-time event subtracted (for EPIC-pn). The brightest source in the north is the SNR 1E0102.2-7219. The observations used for this image accumulate to a maximum exposure of 210 ks (EPIC-pn) and 250 ks (EPIC-MOS) west of the SNR. Typical exposures in other areas are 10–20 ks.

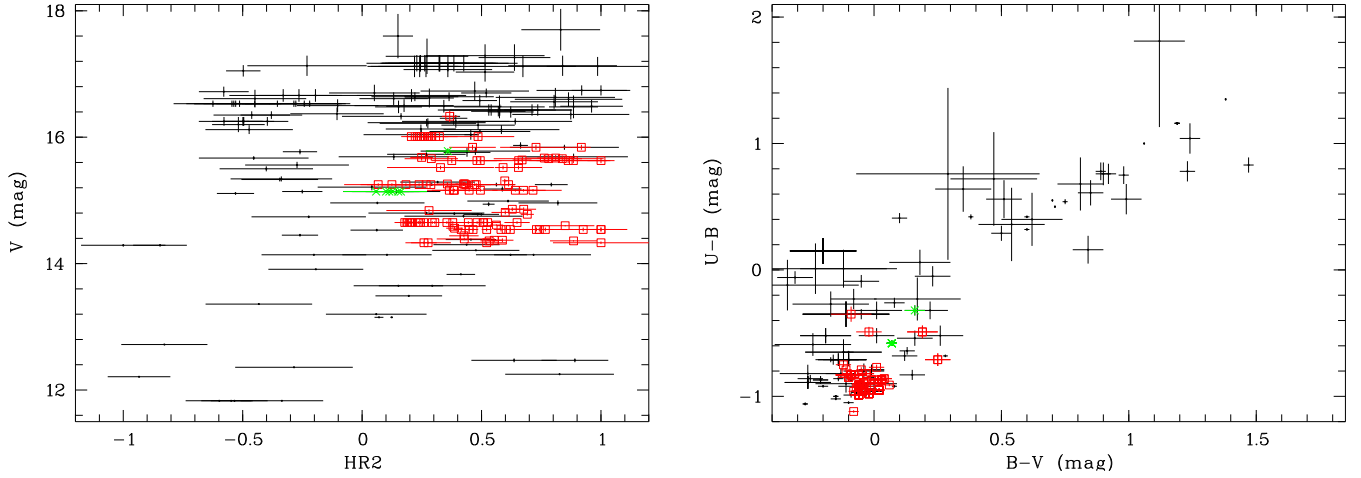


Fig. 3. Correlation of the EPIC source detection list with the optical catalogue of Massey (2002). The nearest star within $5''$ from the X-ray position is used as most likely optical counterpart. Multiple positional coincidences are rare because of the limiting magnitude of $V = 18$ of the optical catalogue. *Left:* V magnitude of the optical counterpart plotted versus hardness ratio 2 (restricted to sources with errors on HR2 smaller than 0.25). X-ray sources which are detected in different observations may appear several times with different HR2 but the same counterpart (V magnitude). Known HMXBs are marked with squares, AGN with x. Only very few AGN (two in the plots) behind the observed SMC fields are as optically bright as HMXBs. *Right:* Comparison of $B-V$ and $U-B$ colour indices for the optical counterparts of the X-ray sources. Known HMXBs in the SMC show typical V magnitudes of 14–16 and are closely concentrated in a small area in the optical colour-colour diagram.

minosity of $1.8 \times 10^{33} \text{ erg s}^{-1}$ for a distance of 60 kpc to the SMC. With this limit, the subclass of persistent Be-HMXBs which shows typical luminosities of around $10^{34} \text{ erg s}^{-1}$ can easily be detected and also it should be possible to detect the first cataclysmic variables in the SMC when they are in bright state (e.g. GK Per was observed with $\sim 10^{34} \text{ erg s}^{-1}$ in outburst during EXOSAT observations; Watson et al., 1985).

Source classifications using hardness ratios and optical information can be used to separate different source types and disentangle the SMC source populations from foreground stars and background AGN. In order to identify possible optical counterparts with high confidence, systematic uncertainties in the EPIC X-ray positions need to be reduced. This work is currently in progress by registering the positions of X-ray sources in individual pointings to an optical coordinate frame using sources with well known counterparts. For this purpose the large number of HMXBs and the increasing number of quasars can be used that are known behind the SMC (see Geha et al., 2003; Dobrzycki et al., 2005, and references therein). First results show that the systematic uncertainties in the EPIC positions can be reduced from typically $2-3''$ to about $1''$.

As example to classify new HMXB candidates we correlated our EPIC detection list (in a preliminary way with unregistered X-ray coordinates) with the optical catalogue of Massey (2002). The X-ray spectra of HMXBs in the SMC are usually characterized by a hard power-law with a relatively narrow distribution of the photon index

(Haberl & Pietsch, 2004). Therefore, the hardness ratio 2 (HR2) value is expected to cover a well defined range. Also their optical counterparts, in the SMC mainly Be stars, show similar brightness and optical colours (Coe et al., 2005). In this way we can define areas in parameter space where sources of given nature (in this case HMXBs) are likely to be found. Figure 3 shows a comparison of the X-ray HR2 with V magnitude of their optical counterparts. The optical $B-V$ and $U-B$ colours (from Massey, 2002) of the optical counterparts are also presented in Fig. 3. As expected the known HMXBs cover well defined locations in these diagrams and new candidate HMXBs can be selected (for similar and additional selection criteria and methods see e.g. Shtykovskiy & Gilfanov, 2005; McGowan et al., 2007b).

4. Conclusions

First results from systematic analyses of X-ray data of the SMC obtained with Chandra and XMM-Newton demonstrate the prospects for X-ray source population studies of the Magellanic Clouds, but also show the demand for a complete survey. The full LMC is probably too large to be completely covered by the relatively small field of view of modern instruments in an acceptable number of observations. In the SMC up to now, particularly the outer regions with older stellar populations and the area of the Eastern Wing are only sparsely covered by XMM-Newton observations. Full coverage is highly desired to derive complete

source samples, probing areas of different stellar ages. Large-scale structures in the diffuse emission can only be investigated in a full survey. EPIC observations with relatively moderate exposure are sensitive down to $\sim 2 \times 10^{33}$ erg s $^{-1}$ for point sources in the SMC. First results from studies of archival data demonstrate that one will be able to characterize individual X-ray sources by their time variability and spectrum, if they are bright enough, and identify and/or classify the sources using hardness ratios, long-term variability, source extent, and information from other wavelengths.

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